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REPORT ON

AN EXPERIMENTAL STUDY ON EVAPORATION AND COMBUSTION OF SINGLE DROPLETS OF CWS (Ph I)

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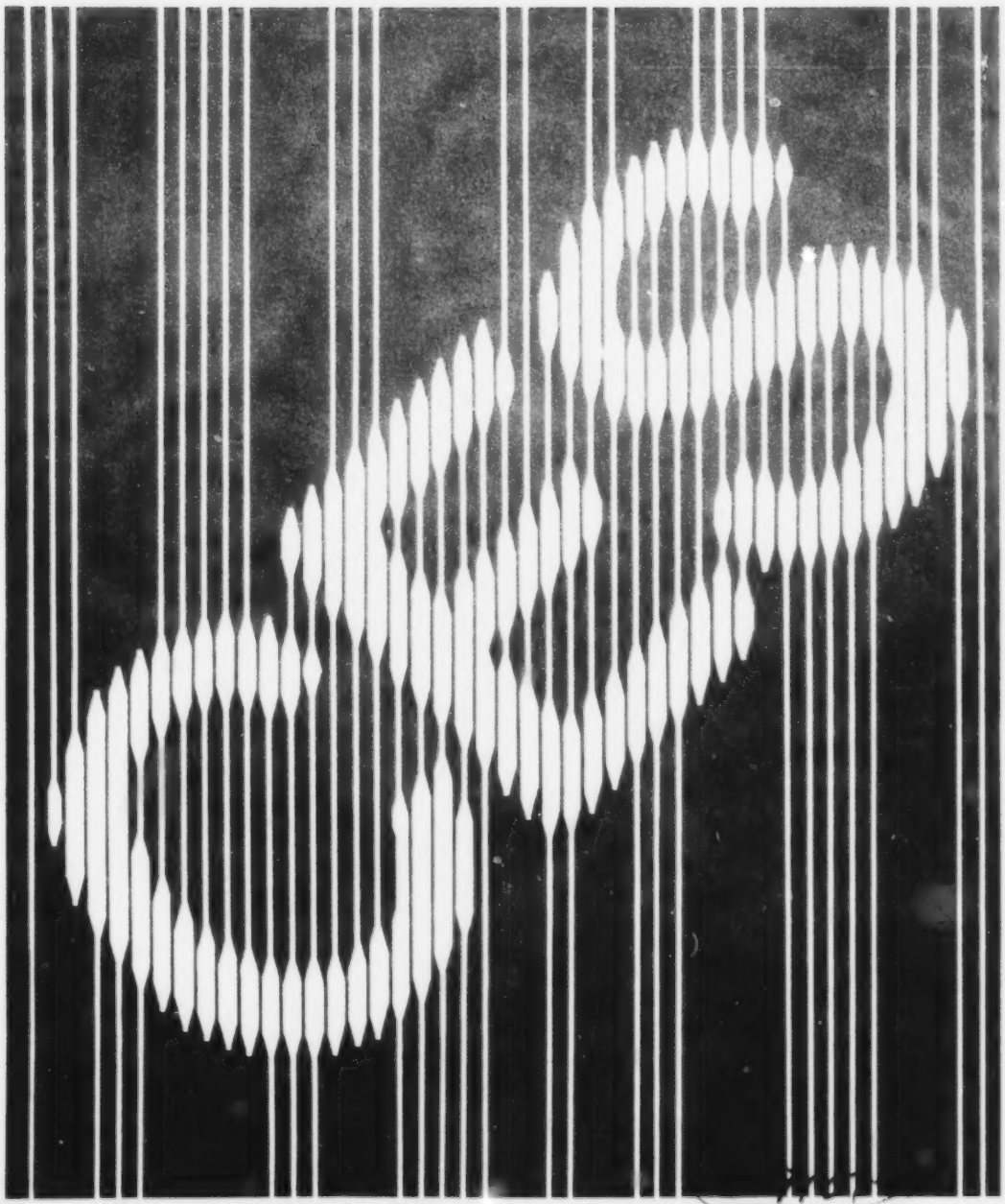

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AN EXPERIMENTAL STUDY ON EVAPORATION AND COMBUSTION OF SINGLE DROPLETS (Phase I) OF CWS

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INTRODUCTION

Solid coal fuel has a long history of useage as the principle fuel for supplying heat energy and generating electric power. Coal firing combustion systems for the two above uses have evolved on a world wide scale over the last hundred years and the technology of both boiler design and operation is well developed. Utility units as large as 500 - 1300 MW output have been operated satisfactorily on coal in many parts of the world. Available coal burning equipment varies from small stoker fired units to large pulverized coal installations. More recently new techniques for burning coal have received attention including various types of fluidized bed combustors. Atmospheric fluidized bed combustion and circulating fluidized bed combustion has received considerable research and development attention.

Solid fuel still suffers disadvantages in comparison with liquid fuel. Liquid fuel has storage, transportation and handling advantages, for example no grinding or milling is required. Boilers firing liquid fuel can have more compact structure as a result of the higher heat transfer efficiency with liquid fuels. Erosion, corrosion and deposition on tube and other heat transfer surfaces is less. However, liquid fuels did not come into widespread use until the early sixties. At that time nuclear energy was beginning to be a viable economic alternative as well and the economics of this latter energy option were based on large units. The economics of large scale coal units may have been noncompetitive against those of coal's two competitors, but what ever cause, coal was displaced from its leading position as the principle energy source. Oil and to some extent nuclear power replaced it in its former traditional areas of application. This new situation did not last long as by the mid 1970's the price of oil had begun a continuous and rapid trend upward and political alignments in the world were threatening the reliability of supply. At the same time experience with the operation of nuclear power plants indicated that the economics were less favourable than predicted and the growing public feeling on nuclear safety resulted in cancellation of plants and the introduction of costly, increased safety measures to those plants under construction or the retrofitting of them to older existing nuclear power plants. All of the above refocussed attention on coal particularly on new ways for the producer to supply it to the consumer. Among the many options such as powdered coal, clean powdered coal and coal slurries, was the coal water slurry CWS. This last was an option that found favour in Atlantic Canada particularly Nova Scotia which had large deposits of coal, no domestic oil and large oil fired utilities. It offered availability and a potential fuel unaffected by world market forces, and possessing some of the advantages of oil.

While CWS superficially looks like a direct replacement for oil some work must be done on the fuel/combustion system combination for it to be burnt satisfactorily. Because the water content of CWS varies from 25 to 40 percent, the large amount of water must have a strong influence on the ignition of the CWS spray, the stability of the flame and the carbon burnout. While the gross rheological properties of the CWS can be made to match those of the fuel oil, dependence on temperaure, shear rate, etc. may differ sufficiently so that burner development is required for optimum atomization of CWS.

The ash content of CWS causes serious erosion problems in nozzles built with conventional materials and for reasonable nozzle life with CWS erosion-resistant materials must be used for critical nozzle parts. The ash can also cause slagging and fouling on heat transfer surfaces as well as erosion/corrosion on the heat exchange surfaces in the convective passages. There is, therefore, a requirement for considerable study and investigation on the mechanism of CWS combustion technology on a world wide scale.

The combustion of CWS droplets, distinguished from the combustion of pulverized coal and the combustion of coarse fuel particles in an FBC,burns fuel with high water content (30 percent usually). Because a certain amount of heat is necessary to evaporate the water content in the CWS droplets before ignition, there is a significant delay in the ignition of CWS. The time required for complete combustion of a char particle (CWS residue) is appreciably longer than that needed for pulverized coal having similar particle size and the same parent coal. This has been proven experimentally by Cao et al [1], Srinivasachar et al [2] and Pourkashanian and Williams [3]. Cen et al [4] have found that the apparent ignition temperature for a CWS droplet decreased due to the presence of water. Obviously, the combustion behaviour of CWS droplets differs from pulverized coal due to their high water content. However, the information concering the influence of moisture on the CWS combustion is lacking. In the case of combustion of pulverized coal, the fuel fed into the combustion chamber is almost dry. The moisture content of screened coal particles fed into the FBC is low and thus time to evaporate the moisture in the screened coal particles is very short compared with the total particle residence time in the FBC's bed. Neither pulverized coal nor fluidized bed combustion has considered the process of water evaporation during precombustion. This process is either ignored or is considered as instantaneous evaporation.

There is some information on the evaporation process of CWS droplets in gas flow published by Cen et al [5],Fu et al [6], Huang [7] and Cheong et al [8]. Some of this work was carried out following the theoretical analysis on the evaporation of liquid droplets proposed by Spalding [9], and improved by Blackshear [10]. The analysis was based on the process of the diffusion of vapor from the evaporation surface to the main gas stream through the surrounding gas film by using Steafan's Law. There also are other models postulated by Zhou et al [11], Huang et al [7] and Cheong et al [8] which con-

sider that water evaporation occurs at a moving interface within the CWS droplet.

The solid loading of CWS usually is about 70 percent. The presence of water (30 percent) in the slurry not only consumes a certain amount of heat released from CWS combustion for its evaporation (about 3-5 percent of total heating value [2,3], but causes the significant delay of ignition [2,3,12,13,14]. Reference [2] also reported that the ignition temperature of CWS is lowered in comparison with that for pulverized parent coal. Reference[15] found that during water evaporation, coal powders in a CWS droplet agglomerate to form a shell with certain mechanical strength. Indeed, combustion characteristics of CWS droplets differ with pulverized coal combustion because of the presence of a high moisture content.

Little work has been done on modeling the combustion process of CWS droplets. It is, no doubt, because of the complex nature of CWS combustion. However, better understanding is necessary to extend the applications of CWS in various areas. Pilot and demonstration firing tests are currently being carried out to this end. In many countries, the majority of work done was centered on the ignition and stability of flame, atomization and burner design and rheological properties of the fuel. This is because the potential application of CWS at present seems to be a direct replacement of utility boilers originally designed for burning fuel oil. The fundamental research dealing with evaporation devolatilization and char combustion is still lacking. Therefore, investigation of the combustion of single suspended and freely falling droplets can provide much valuable information.

PREVIOUS WORK

In the common method of studying the combustion process of a single droplet, the single CWS droplet is suspended on the tip of a fine thermocouple or fibre wire [3,5]. The weight loss of the droplet is measured continuously; its temperature history is recorded; and the appearance of the droplet is monitored by a high-speed camera. The suspended droplet is put in a hot environment heated by convection and radiation and the temperature is time dependent. Currently, some investigators [16] are using a laser beam to heat the droplet directly. Of course, the relative gas flowrate and atmosphere also can be altered depending on the nature of the experiment. Thus, devolatilization and char combustion, or even pyrolysis of CWS droplets in an inert atmosphere can be studied by this method.

Free-falling particles through a vertical tube furnace is another approach which was used to evaluate the combustion characterestics of pulverized coals [17,18,19]. Currently, only a few investigators have evaluated the combustion of CWS droplets in this way [20]. CWS droplets of different sizes and feed rates are produced by a certain kind of feeder and then passed through the tube furnace and are

quenched and collected at the bottom of the furnace. The residence time of the droplets in the furnace is varied by changing the furnace height. The residual char collected is used as a tracer to indicate the history of CWS droplet combustion. The environment temperature and atmosphere can also change along the furnace length to provide different conditions for evaporation, devolatilization, char combustion or pyrolysis in an inert atmosphere.

A third method used to investigate the evaporation and ignition of CWS droplet is the use of a hot surface. The droplet contacts the hot surface and is heated up to evaporation and/or ignition. This technique is used in investigations of internal combustion engines, especially to study the droplet evaporation process. However, to date, no reporting of investigations for CWS droplets using this method have been found in the literature. The mechanism of heat transfer with this method is also not representative of its combustion behaviour in a flame.

THEORETICAL ANALYSIS

The current understanding of CWS droplet combustion assumes a series of sequential reaction stages. These are the evaporation of water, volatile evolution and ignition and combustion of carbon residue. In comparison, the process of water evaporation in PC/FBC combustion is either ignored or is considered to be an instantaneous process. Thus the primary difference encountered when modelling the combustion behaviour of CWS droplets stems from the additional time required for the droplet drying process.

Water Evaporation

There are two concepts which may be used to model water evaporation. The first is external surface evaporation. The evaporation of water contained in a CWS droplet only occurs at the external surface of the CWS droplet. Vapor produced diffuses through the stagnant gas film surrounding the droplet. Water in the interstices of the solid matrix of a CWS droplet replenishes the external surface. The evaporation lasts until the total amount of water is consumed. References [2,13,14] adopted this concept to model water evaporation. The boiling temperature is assumed as the evaporation temperature at the external surface [13]. However, the wet-bulb temperature (saturation temperature) has also been adopted as the equilibrium temperature at the evaporation surface in the other studies.

The second is the internal surface evaporation (i.e., the two-zone model). With the progress of evaporation, a receding internal evaporation surface gradually moves to the centre of the wet core of the CWS droplet, and a drying shell (zone) appears outside of the wet core. Heat from the environment transfers through the dry zone, by

conduction, to reach the internal evaporation surface. Meanwhile, the temperature in the dry zone increases due to heat transfer. Vapor produced at the internal evaporation surface diffuses via the solid matrix of the dry zone and enters the gas phase external to the particles. References [3,8,11] selected the two-zone concept to model the evaporation process of CWS droplets. Reference [8] assumed the pseudo steady state in the dry zone for simplification and assumed that no heat would be dispersed in the dry zone. With the use of the two-zone model allowances to model the volatile decomposition in the dry zone are necessary in addition to the process of water evaporation at the receding internal interface.

Devolatilization

Considerable research on the devolatilization of coal under fast pyrolysis has been conducted. Various kinetic models of volatile decomposition have been proposed. Currently, the kinetic models of devolatilization of CWS droplets basically follow models developed for coal pyrolysis. The kinetic model for volatile decomposition in references [2,14] were expressed as an overall reaction model similar to that initially proposed by Badzioch [21]. The rate of devolatilization is modelled by the use of two, parallel, first-order reactions in reference [3]. It is believed that this model is virtually identical to that proposed by Stickler et al [22]. Anthony et al [23] postulated a complex model which suposed that pyrolysis occured through an infinite series of parallel reactions. Reference [24] applied the concept to model coal combustion in fluidized beds.

A common feature of the various devolatilization models is that the temperature history must be specified before the temperature-dependent kinetics for coal pyrolysis may be calculated. This implies that the devolatilization equations must be closely coupled to the heat/mass transfer processes. Then, the solution of the coupled equations will provide a description of temperature history and volatile evolution.

Residue Char Combustion

It is commonly believed that the hetrogeneous reaction between the char residue and oxygen is probably controlled by several factors. Important parameters reaction include the temperature, particle size, relative velocity between particle and gas stream as well as the environment pressure. The overall reaction rate as postulated by Gray [25] and Field [26], is commonly accepted as an accurate description of the kinetics of char combustion. The combustion of carbon residue, will, generally speaking, be controlled by a combination of bulk diffusion and pore diffusion as well as by the intrinsic chemical reaction rates. Distinct reaction regines whether mass transfer, reaction documinated, or by both can be identified for char particles.

For combustion of char residue in CWS, reference [13] considered that char oxidation rate was boundary layer diffusion limited and

adopted the Field [26] formula as the rate expresssion. Reference [3] also employed the overall rate expression derived by Field [26]. The controlling resistances for diffusion include both bulk difffusion and pore diffusion. Reference [14] used a model which assumed both diffusion and chemical reaction control. Reference [2] tried to find the oxygen concentration at the external surface of a particle by using as an overall transfer resistance expression, which was then applied to the chemical reaction rate experession.

Most of the work mentioned above considers carbon monoxide as the dominant product of CWS char combustion. The carbon monoxide is then assumed to further oxidize to carbon dioxide. The effect of water vapor on char ozidation kinetics was not memtioned in the above papers.

Since the overall combustion process for CWS can basically be postulated as involving three consecutive stages, the features (physical model) of combustion of CWS droplet can be described as follows.

Evaporation of Moisture

It is believed that the combustion of CWS must be significantly influenced by the presence of water because of a high water content in the CWS droplets. The heat released from CWS combustion is partially consumed to evaporate the existing water. Therefore, the combustion temperature of CWS should be lower and the ignition of CWS is delayed significantly [2,3,12,13,14]. However, the ignition temperature observed in combustion experiments on single droplets is low compared to that of the parent coal particle [15]. The presence of water vapor will act as a catalyst for the oxidation of carbon monoxide. However, it is also not clear that the reaction of steam with carbon in CWS combustion can be ignored.

The overall process of water evaporation of a single CWS droplet can be considered to be governed by both heat and mass transfer. A moving internal evaporation surface recedes towards the centre of the droplet. The heat flux reaching the external surface from the environment by convection/radiation conducts into the dry zone of a CWS droplet and raises the temperature in the dry zone. A fraction of the heat from the environment evaporates the water at the moving internal evaporation surface. Steam generated here escapes to the environment by two subsequent transfer processes: diffusion in the pores (interstices) of the CWS droplet and diffusion in the stagnant gas film surrounding the droplet. The temperature at the internal evaporation surface remains at the equilibrium temperature (saturation temperature), and the temperature in the wet core basically keeps the initial temperature of the CWS droplet.

Based on the above understanding, Zhou et al [11] postulated a mathematical model for the evaporatíon process in CWS droplets.

Volatile Devolatilization

The decomposition of volatiles occurs under rapid heating conditions for most combustion cases. As revealed by previous studies on pulverized coal combustion, the heating rate has a strong influence on volatile evolution. At low heating rates, pyrolysis (of bituminous coal) usually starts at 300°C-400°C; but at 1000°C/sec it starts at 900°C and at 10,000°C/sec it starts at 1100°C [25]. The volatile yield is also influenced by the heating rate [25].

Devolatilization is also affected by the particles size. For pulverized coal pyrolysis, if the particle size is less than 100 micrometers, it is believed that devolatilization is particle-size independent [25]. Individual coal particles within CWS droplet will agglomerate (particularly for caking coals) to form a cenosphere with a larger diameter during the moisture evaporation and devolatilization stages. In view of the agglomeration behavior, it is believed that the devolatilization process for CWS is independent of the particle size, unlike the records noted for pulverized coal.

Different kinetic models of thermal decomposition from simple series rate expressions to complex ones with several parallel coupeling reactions [2,3,12,13,14] have been postulated. For practical use, the complex model is limited by the need to use a large number of rate constants which often vary for different coals.

As soon as the temperature in the dry zone rises, the thermal decomposition reactions commence. However, the rate of thermal decomposition of volatiles is estimated to occur in a time scale an order of magnitude slower than the heatup rate [3]. The dry zone of CWS droplets can thus be raised to higher temperatures without significant devolatilization. From this observation, it may be assumed that moisture evaporation and devolatilization occur sequentially.

Char Residue Combustion

After thermal decomposition of volatiles, the heterogeneous reactions occur between the char residue and reactants. In most cases of practical significance, the char oxidation reaction initially undergoes partial oxidation to form carbon monoxide [28]. The carbon monoxide further oxidizes in the gas phase to carbon dioxide. This reaction is very fast and is accelerated by the presence of water vapor which acts as a catalyst. As estimated by Walker [29], the char-water reaction can be neglected.

The combustion of char residue of CWS droplets is at least, partially controlled by chemical reaction. The heterogeneous reactions of char-oxygen occur not only at the external surface of the char residue, but also in the internal surface or pores role for complete consumption of the CWS droplet. In a review of pulverized coal combustion Gray [25] concludes that for small coal paticles, the chemical reaction rate is the rate controlling step. Hence, it is believed that for comparably larger particles, the combustion of CWS droplets

occurs under chemical and diffusion control.

In a way similar to the combustion of pulverized coal, the agglomerated char particles break into several fragments during the final burnout phases of char combustion.

There is a slight overlapping between the devolatilization of volatiles and the combustion of char residue [4]. The overlapping might be dependent upon the droplet size, volatile content and the solids loading.

The overall model of CWS combustion has also been developed by Zhou et al. More details can be found in reference [27].

EXPERIMENTAL INVESTIGATION

The experimental work comprised two phases:

1. Setting up a CWS droplet generator.

2. Studying the evaporation and combustion of CWS in a drop tube furnace.

PHASE ONE: Laboratory CWS Droplet Generator and Some Factors that Affect the Droplet Size of CWS

With the free-falling method of studying the evaporation and combustion ofcoal-water slurry, the devolpment of a feed system is a key issue. The feederuses a syringe which is coupled to a motor drive and is mounted on the top of the vertical tube furnace. It generates the CWS droplets to provide a monodisperse CWS droplet stream of uniform droplet size and composition. Previous investigation [30] revealed that the droplet size and its solid loading greatly affect the evaporation and combustion of CWS. To simulate the real combustion process of CWS in the boilers, droplet sizes smaller than 0.5-1 mm are necessary. In addition, the solid loading in the CWS droplets should be close to 70 percent, i.e., the usual value of solid loading for CWS firing in boilers. Due to the requirement to produce a monodisperse CWS droplet stream,the usual atomization methods cannot be employed here, and a hypodermic syringe arrangement has been used to generate the CWS droplets.

The Morgantown Energy Technology Centre (METC), USDOE, has developed a laboratory CWS droplet generator based on the US patent of Zoltan which was originally developed for ink-jet printers [30]. However, they used very fine powdered coal where the top size of coal particles was under a certain value in their CWS. Thus, they could use an extremely fine orifice to produce the CWS droplets with 100 μm

- 300 μm diameters without any plugging of the hypodermic. The solid loading in their experiments was 40 percent which was much lower than practical concentrations for CWS. A piezoelectric element was used to periodically squeeze the CWS through the small orifice.

In the work reported, attempts were made to use medical syringes with needles of various diameters. Comparison trials were made to explore the relationship between the droplet size and parameters such as needle diameter; pump speed and solid loading, and with different homogeneous fluids to evaluate the influence of fluid properties on the atomization process. An analytical prediction to calculate the droplet size was also developed and predicted values were compared with the experimental data.

Equipment

Figure 1 shows the CWS droplet generator. The syringe piston is pushed by a syrings pump, moving it inward at a constant rate. The droplet forms beneath the needle tip. The pump speed can be adjusted to a number of different predetermined values.

The syringe capacity used in this work was 50 cc and the inner diameter was 25.8 mm. The needles used to generate CWS droplets were standard stainless steel needles designated No. 3 and No. 4. The No. 1, 2 and 5 needles were used for distilled water only. Table 1 gives more details about the needles.

Table 1. Characteristics of Needles used in Equipment

Needle No.	External Diameter	Inner diameter	Material	Comments
1	1.695	0.605	plastic	plug immediately for CWS
2	1.125	0.580	steel	
3	1.673	1.138	plastic	
4	2.228	1.138	plastic	
5	0.571	0.040	steel	

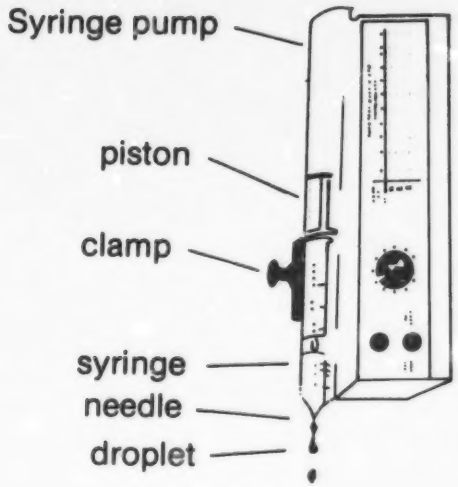

Figure 1. Coal-Water Slurry Droplet Generator

Slurry

The CWS used had been stored for considerable time and had already segregated. This slurry was the only one available at CES when the work was done. It was stirred to get the segregated material back in suspension and water was added to obtain slurries with different solid loadings. The ash content of the original material was 8.5 percent on a dry basis. The densities of slurries with different solid loadings are shown in Table 2.

Table 2. Densities of Slurries

g/cm^3

Slurry Sample		1	2	3	4	Average
Solid Loading	65%	1.196	1.199	1.190	1.190	1.194
	60%	1.174	1.175	1.176	1.170	1.174
	55%	1.154	1.150	—	—	1.152
	50%	1.110	1.110	1.113	—	1.111

It was also shown that the surface tensions of slurries affects the droplet size. The surface tension of the slurries used were measured and are shown in Table 3. For comparison, the surface tensions of distilled water, salt water and soapy water have been listed in Table 3. All values are an average of a number of repeat measurements and were obtained using a DeNOUY Tensiometer. In Table 3, the values in the numerator are readings measured by the Tensiometer while the others in the denominator are relative values based on the readings obtained for distilled water. The actual surface tensions were obtained by multiplying real values of the surface tension of dis-

tilled water (in this study, it is equal to 0.0731 N/m) by relative values shown in the denominator.

Table 3. Surface Tensions

Distilled Water	Salt Water 6.58%	Soapy Water	Coal-Water Slurry (Different Solid Loading)			
			50%	55%	60%	65%
20.94/1.000	23.675/1.130	10.533/0.503	17.067/0.840	18.214/0.870	18.829/0.899	23.12/1.104

Prediction of Droplet Diameter

As observed in experiments, droplet size is strongly dependent on the needle diameters (inner and outer). In order to simulate the evaporation and combustion of CWS droplets with different diameters in the vertical furnace, it is necessary to develop a method to predict the droplet size. In the actual case, the measurment of particle size as it moves in the hot furnace is not easy. However, an expression based on the following conditions will be derived.

The droplets form just beneath the needle tip and remain suspended until they drop off. Based on the balance of forces acting on the droplet, the droplet diameter at separation can be found. Figure 2 shows these forces acting on the droplet. It is seen that two forces act on a droplet. One tries to keep the droplet beneath the tip of the needle; the other favours droplet detachment. The latter is due to the action of a gravity force on the droplet while the surface tension between the liquid (CWS) and needle surface (the external surface of the tip) serves as a cohesive force which prevents droplet detachment.

Considering that the liquid is squeezed by the syringe piston at a unique (constant) moving rate, the force acting on the liquid in the syringe, must be balanced by the friction existing between the syringe wall and the liquid. According to Newton's Second Law, and with no detectable momentum in the droplets formed at the tip, there should be no additional force affecting the droplet suspended beneath the needle tip.

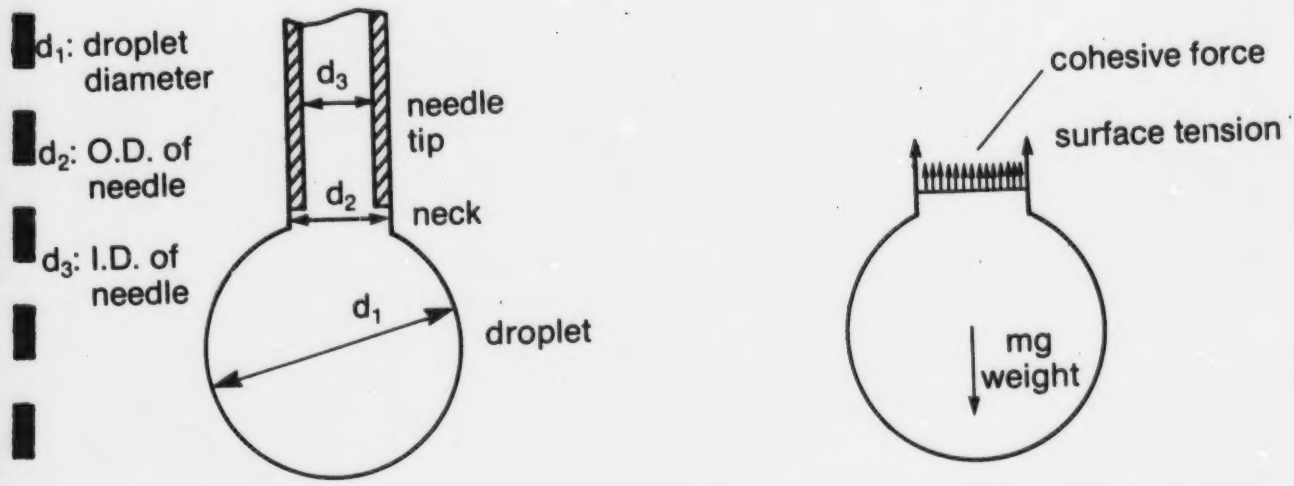

Figure 2. Forces Acting on a Droplet

The gravity component of force on the droplet (weight) increases gradually because of the continuous addition of liquid into the droplet. The criteria for droplet separation should be considered as:

Surface Tension (Cohesive Force) $\leq$ Gravity of Droplet (detaching force)

The balance of forces on a droplet can be expressed as:

$$\pi \tau d_2 \cos\theta = \frac{\pi}{6} d_1^3 \rho_g$$

or

$$d_1 = \sqrt[3]{\frac{6\tau d_2 \cos\theta}{\rho_g}}$$

Thus, the droplet diameter can be predicted from known solution and needle parameters,

where τ is the surface tension

ρ is the liquid density

d_1 is the drop diameter (mm)

d_2 is the outer needle diameter (mm)

θ is the contact angle.

Results and Discussion

The results presented are from tests of slurries of four different solid loading. Tests in salt water, soapy water and distilled water were conducted for comparison. The other variable parameters were needle size (inner and external diameters) and piston velocity. The droplet size was calculated from the rate of droplet fall and volume difference (i.e., total amount of CWS fed in a certain period).

The problem with generating the droplets by this method was plugging of the needles. Since the top size of coal particles in these slurries was not limited, the large particles easily plugged the needle. The particle distribution in the slurry was not analyzed in this work. However, according to finger tactility, these slurries contain coarse particles with a diameter of at least 500μm. Due to this problem, a small size needle could not be used to produce the CWS droplets with a diameter of less than 2 mm. Generally, the extrusion rate, i.e., velocity of the syringe piston, has only a slight influence on the droplet size. If this rate was too high the monodisperse droplet stream could not be maintained.

The initial data were plotted as relative droplet diameter versus the extrusion rate. The results showed a high degree of scatter. Then the data were plotted as the relative droplet size versus the dimensionless groups of parameters shown below, and trends became clear.

The first dimensionless value $K^2U_o\rho D_o g/9.81$, in Figure 3, indicates the ratio of the gravity of CWS droplet versus the surface tension where K is theratio of inner and outer diameter of the needle. According to the analytical model, these two factors control the droplet size suspended beneath the tip of the needle. The data obtained by using four different solid loadings can be plotted in a straight line for only a certain needle size. However, the data obtained using a different needle size for the same loading cannot be plotted in a straight line. The data for the water droplets, i.e., zero loading cannot be plotted in the same straight lines as shown for CWS droplets.

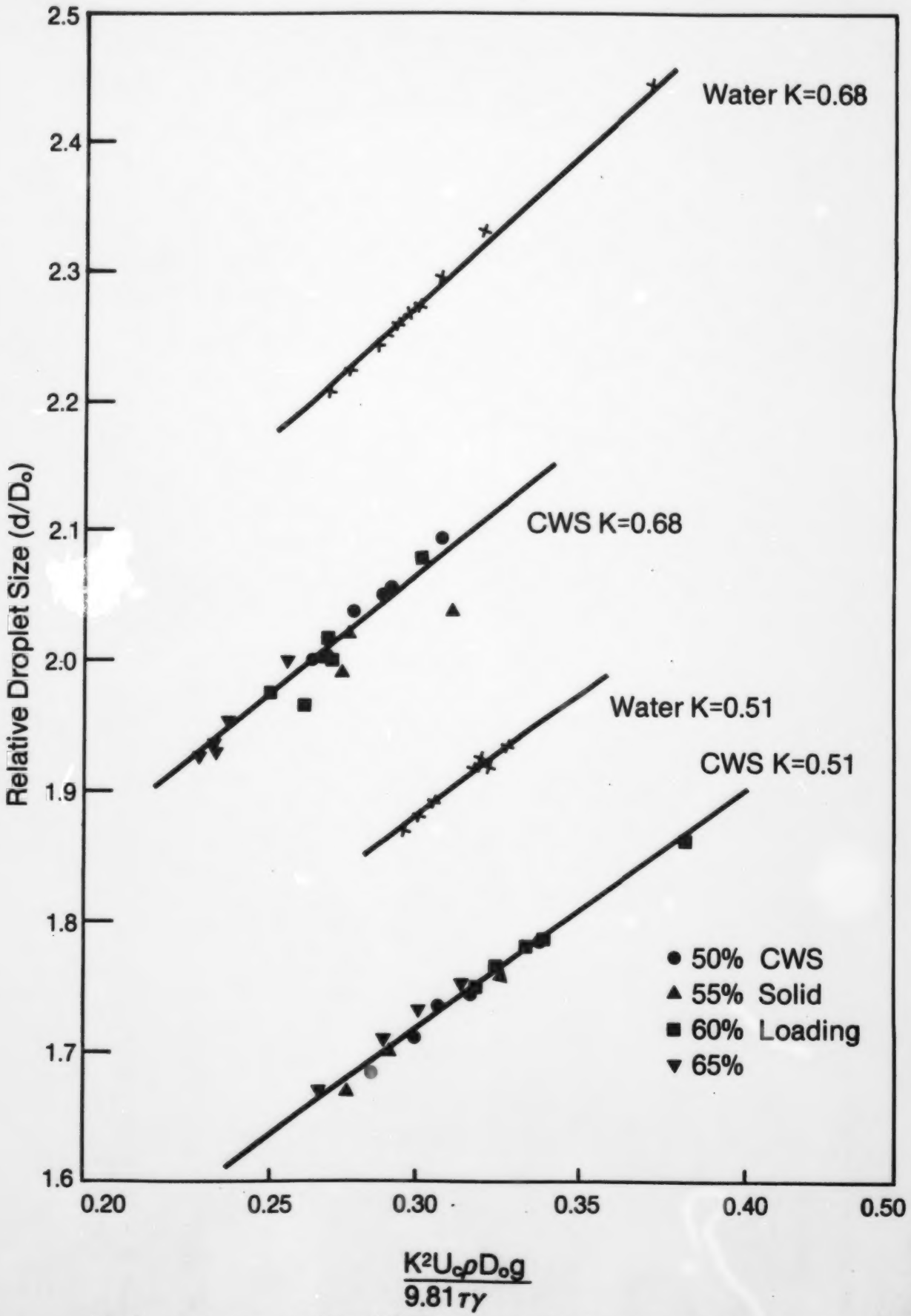

Figure 3. Relative Droplet Size versus $K^2U_c\rho D_o g/9.81\tau\gamma$

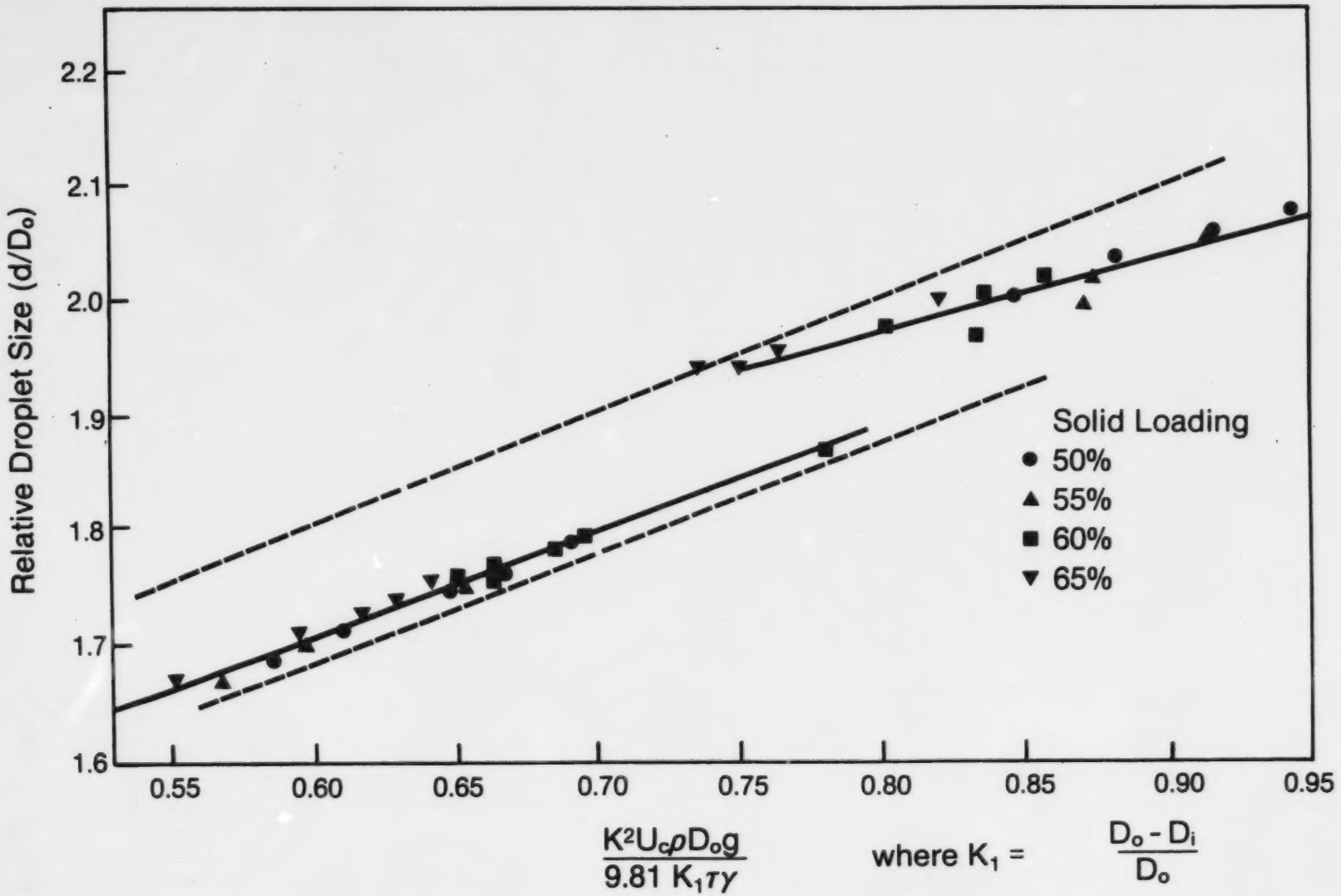

Figure 4. Relative Droplet Size versus $K^2 U_c \rho D_o g / 9.81 K_1 \tau \gamma$

Figure 4 shows all the data for CWS droplets produced by different needle sizes. The dimensionless value at the horizontal axis is revised by multiplying by a factor $K_1 = (D_o - D_i)/D_o$, which is the ratio of thichness of needle versus internal diameter.

The improvement in the data fit might be explained as follows. The data fit in Figure 3 is based on the assumption that the surface tension keeping the droplet beneath the needle tip is only determined by the internal/outer diameter of the needle. In fact, the surface tension is influenced by the needle thickness. When the thickness of the needle is considered, the data in Figure 4 reveals a much better fit than those shown in Figure 3.

PHASE TWO: EVAPORATION AND COMBUSTION EXPERIMENTS OF CWS DROPLETS

The study of the evaporation and combustion of CWS droplets was conducted in two vertical tube furnaces. The CWS droplets generated by the droplet feeder described fall freely from the top, down through the hot zone, and evaporate and decompose slightly. The residual char is collected at the botom of the furnaces. The residual char particles were weighted, analysed, etc., and some were dropped through the tube furnace for further burning.

The collected char samples were analysed to provide data on the changes of droplet condition with time. The work fitting the data to a mathematical model is underway.

Facilities

The furnaces used in this study belonged to the Combustion and Carbonization Research Laboratory (CCRL), Energy Research Laboratories, CANMET. Figure 5 shows the large furnace. This furnace is made up of four elementary zones. Each elementary zone consisted of an individually electrically heated system. The zones can be controlled by computer to any desired temperature. The high limit of temperature was 1600°C. The furnace was insulated and housed in a steel container. The overall height of the column furnace was 2.0 m. The combustion chamber consisted of four pieces of ceramic pipe of 70 mm/65 mm in O.D./I.D. Thermocouples were placed on the internal surface of the ceramic tube to measure the temperatures. Due to chimmey effect, the lowest zone of furnace cannot be heated up to 1600°C.

The smaller furnace used in this study was heated electrically. The two heating zones were controlled individually. The temperature limitation was 1400°C for both zones. The total height of the furnace

was 1.5 M. A quartz tube with 23.54 mm I.D. was put in the centre of the furnace and served as the combustion chamber. The wall temperatures of the Quartz tube were measured. The temperatures in two zones could be adjusted to any desired level, but in practice, it proved difficult to maintain the temperatures at the desired set point.

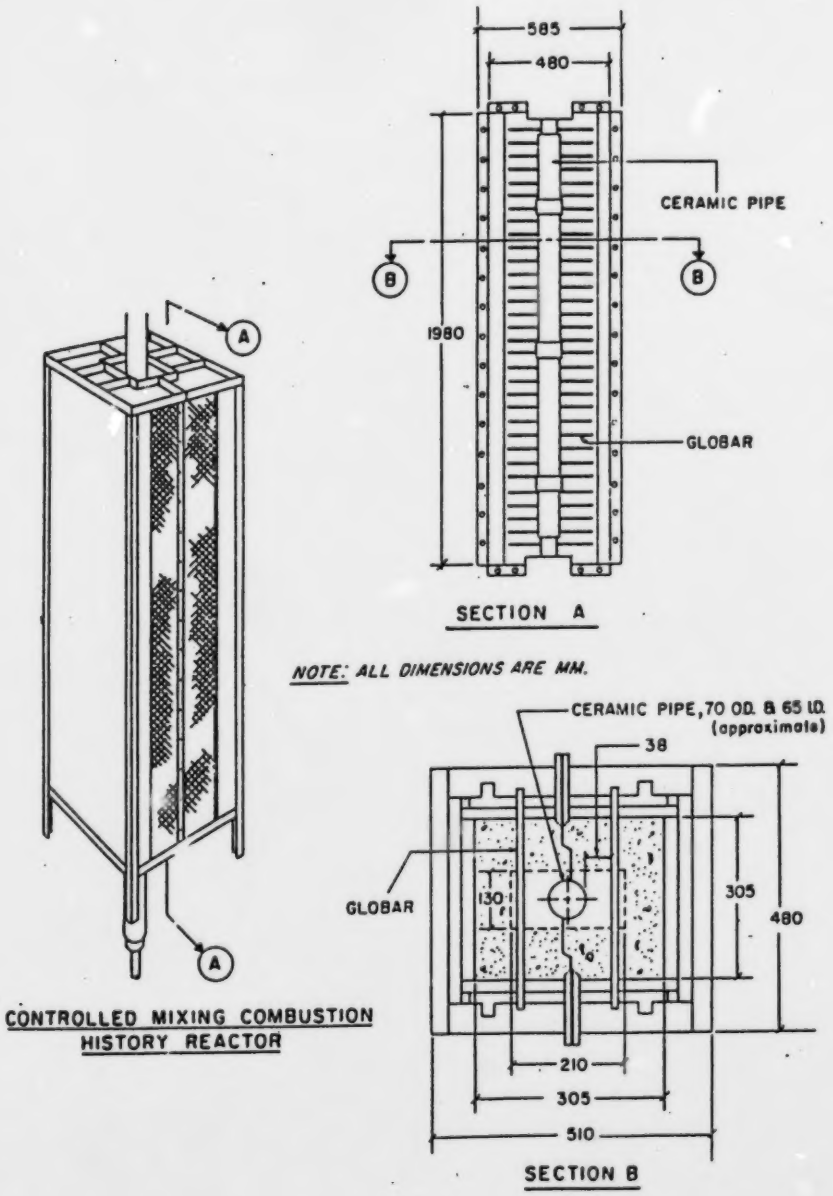

Figure 5. CCRL Furnace

Both furnaces could be purged with a nitrogen stream to study coal pyrolsis.

Coal-Water Slurry Fired in this Study

The trial coal-water slurry for the single droplet test was obtained from the Tunnel Furnace Trials at CCRL. The moisture of CWS was 27.08 percent. The following tables give details of the fuel.

Table 4. Proximate Analysis %

	Moisture	Ash	Fixed Carbon**	Volatile Matter
As Received*	0.82	5.13	57.69	36.46
Dried	0.00	5.17	58.07	36.76

* After Air Drying
**By Difference

Table 5. Ultimate Analysis %

	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen**
As received*	79.70	5.02	1.51	2.15	5.67
Dried	80.36	5.06	1.52	2.17	5.72

Table 6. Ash Fusability Temperature °F

	Initial	Spherical	Hemi-Spherical	Fluid
Reducing	1895	1955	2115	2390
Oxydizing	2455	2588	2605	2620

Table 7. Major Ash Constituents %

SiO_2	Al_2O_3	Fe_3O_3	TiO_2	P_2O_5	CaO	MgO	SO_3	Na_2O	K_2O	BaO	SrO
34.15	18.41	39.95	0.92	0.00	2.19	0.68	0.00	0.41	1.11	0.09	0.08

The heating value was 14368 and 14505 Btu/lb respectively for the as received and dried basis fuel. The free swelling index was 8.5. However, the information about additive and particle size distribution in the slurry was not provided. For comparison, pulverized coal with a similar particle size th ough not of the same type as the parent coal in the slurry was burnt in the large tube furnace. The "coal valley" sample was sieved to obtain two mono-sieve fractions: coarse (-3.35 + 2.00 mm) and fine (-2.00 + 1.70 mm). Their average diameters were close to those CWS droplet sizes generated by using needles 3 and 2. The proximate analysis of the "coal valley" coal is given in Table 8.

Table 8. Proximate Analysis of "Coal Valley" %

Moisture (as received)	Ash (dry)	Volatile Matter (dry)	Fixed Carbon (dry, by diff.)
6.04	10.50	33.39	56.11

In order to generate smaller droplets without the needle plugging, the as received slurry was sieved (passed through a 250 mm mesh). With removal of the large particles in the CWS, the solid loadings of the slurry changed, as shown in Table 9.

Table 9. Proximate Analysis of Fine Coal-Water Slurry (dry base) %

	Moisture	Ash	Volatile Matter	Fixed Carbon
Without filtration	27.08	5.17	36.76	58.07
After filtration	34.41	5.25	36.25	58.50

Also, the proximate analysis of the fuel for reburning trials is shown in Table 10. The fuel was collected at the furnace bottom. The droplets falling through the furnace experienced moisture evaporation. The dried droplet/char particles were ellipsoidal, with a 3.5 mm average diameter.

Table 10. Proximate Analysis of Reburning Fuel %

Moisture	Ash	Volatile Matter	Fixed Carbon
1.15	5.51	35.57	57.77

Attempts were made to dilute the slurry being used by adding distilled water and some experimental data was obtained by using the diluted slurry. However, the initial moisture content of this kind of slurry was not determined. Two sizes of pulverixzed coal were fired in the large furnace and the reburning of evaporated droplets was also conducted. Fine (filtered) slurry was used to generate smaller droplets. The variables in this study were droplet size, temperature profile along furnace axis, moisture content ofdroplet as well as the kind of fuel fed.

Experimental Results

The samples collected were analyzed to obtain experimental data such as moisture and volatile contents. The data were normalized on a certain base for comparison. Table 11 shows the results from the small furnace.

Table 11. % Conversions of Moisture and Volatile at Various Temperature Profiles

	Temperature Profile °/C (upper/lower zones)					
	900/900°C	1000/1000°C	1100/1000°C	1100/1100°C	1200/1100°C	1300/1200°C
Moisture	26.15	62.89	48.39	59.72	36.71	47.94
Volatile	10.06	18.23	15.57	10.43	8.61	19.32

The diameter of the droplet was around 3.35 mm. The initial moisture and volatile contents were 31.99 percent (as received) and 36.81 percent (dried base), respectively. It should be noted that it was very difficult to keep the falling droplets free from the wall of the quartz tube because the long tube had already bent due to expansion. The falling droplets touched the wall of the quartz tube occassionally. This resulted in a longer residence time for evaporation and combustion. This will explain the scatter noted in the data shown in Table 11. As shown in Table 11, some volatile decomposition also occurred during moisture evaporation.

Table 12 lists the data obtained from the large furnace. This furnace has four individual heating zones so the temperature profile along the furnace axis is written from the top down. The data shown in Table 12 (or Table 11) reveals that the `chimney or gas bouyancy effect has a strong influence on the evaporation of moisture. This will be discussed in detail later.

Table 12. % Conversion of Moisture and Volatile at Various Temperature Profiles

		Temperature Profiles (4 zones, from the top to down)		
		1100/1500/1500/1300°C	1500/1500/1500/1300°C	1300/1300/1300/1200°C
350 mm	moisture	78.17%	46.34%	26.84%
droplet	volatile	12.37%	14.14%	---
400 mm	moisture	54.04%	35.90%	---
droplet	volatile	11.90%	13.83%	---

The results obtained from fine CWS trials are listed in Table 13. As seen again, a higher temperature in the tube of furnace did not increase the conversion efficiencies.

Table 13. % Conversions of Moisture and volatile at Various Temperature Profiles

		Conversions under these Temperature Profiles, °C	
		1500/1500/1500/1300°C	1300/1300/1300 1200°C
Fine CWS Moisture 34.41% Volatile 23.77% Droplet size 3.00 mm	Moisture Volatile	68.05 12.50	80.29 --

For comparison, pulverized coal was burnt in the large furnace. Table 14 shows the data.

Table 14. % Conversions of Moisture, Volatile and Fixed Carbon

Pulverized Coal	Particle Size mm	Constituents	Conversions under the Temperature Profile %
			1500/1500/1500/1300°C
"Coal Valley" Initial Constituents Moisture 8.05% Ash 9.00% Volatile 30.29% Fixed Carbon 52.66%	Fine -2.0 +1.7	Moisture Volatile Fixed Carbon	83.03 60.90 26.11
	Coarse -3.35 +2.0	Moisture Volatile Fixed Carbon	83.68 8.89 1.56

Table 15 gives the results for the reburning of the once through dried CWS droplets.

Table 15. % Conversion of Moisture, Volatile and Fixed Carbon

Dried droplets collected at the bottom of the furnace		Dried Granule Size - mm	Constituents	Conversions under the Temperature Profile %
				1500/1500/1500/1300°C
Moisture	1.15%	-3.35 + 2.0	Moisture	23.05%
Ash	5.51%		Volatile	33.59%
Volatile	33.57%		Fixed Carbon	1.26%
Fixed Carbon	57.77%			

DISCUSSION

The preliminary experimental results obtained from both small and large tube furnaces, are insufficient to reveal the nature and mechanism of CWS evaporation and combustion. Measured data seem to be scattered and not accurate. However, these experiments still provide valuable information. The strong influence of moisture on the combustion of slurry is indicated. Ignition, volatile decomposition and char residue combustion of slurry droplets were obviously delayed compared to the combustion of pulverized coal. Also, the experimental method, i.e., free-falling droplets in a vertical tube furnace, was shown to be valid.

Generally speaking, because of larger droplet size, the residence time of the droplet in the tube furnace was too short to realize complete combustion. Most of the experiments did not progress beyond the evaporation stage of the CWS droplet. If one can limit the maximum size of coal particles in the slurry, the smaller droplet then generated by extruding slurry through a small orifice will probably result in more complete combustion. Information dealing with devolatilization and char residue combustion, it is believed, will then be produced.

Residence Time, Manner of Heating Droplet

An adequate residence time of fuel (droplet/particle) in the furnace ensures the droplet/particle will achieve the complete combustion. In the case of the CWS droplet burning in the tube furnace, evaporation of moisture, decomposition of volatiles, ignition of slurry droplets as well as burnout of char residue will occur in succession with some overlapping of each stage. Due to a strong dependence of complete combustion on the size of the droplet/particle, different reaction regimes (diffusion/chemical) steps will govern combustion reactions for different sizes of droplets/particles. Generally, the larger droplets/ particles need a longer time than smaller ones under the same conditions to complete the high conversion of combustible matter in a furnace.

As observed in the reported experiments, because the residence time (or droplet size) was inappropriate, in most cases, only evaporation occurred. The complete combustion of the droplet has not been realized.

By approximate estimation, considering only the free-falling motion and neglecting the chimney effect, the residence time in the small furnace (overall height 1.5 m) was estimated at 0.55 sec. In the large furnace (overall height 2.0 m), it was 0.64 sec. During the droplet's fall from the top down, the droplet was heated both by radiation from the tube wall and convection from environment gas. By approximate calculation, the radiation contribution constituted about 2/3 of the total, depending on the furnace temperature. The process of heating the droplet is a transient and unsteady heat transfer mode. Therefore, heat flux reaching the internal surface of the droplet will be conducted into the core of the droplet. The average temperature of the droplet, as an approximate estimate, only increased to 150°C 250°C for the duration of the time the droplet was in the furnace. This temperature is very much lower than the volatile ignition temperature.

As previously mentioned, both radiation and convection processes transfer heat to the droplet. However, due to natural convection in the tube furnace, there is a stream from bottom to top. This is the so-called chimney effect. The hot air flows in the opposite direction of the free falling drop. The relative velocity between gas and droplet varies. The convective heat transfer coefficient is basically dependent upon the relative velocity. Meanwhile, the increment of relative velocity boosts the drag force. The drag force always offsets the influence of gravity of the droplet. It will increase the droplet residence time. The influence of the chimney effect on the convective heat transfer is not simple and monotonous but complex and multiple. As seen from experimental results shown in Tables 11, 12 and 13, higher furnace temperature does not always result in higher conversion of moisture. Further increment in the furnace temperature, however, causes decrease in the conversion of moisture. The reason for this phenomena might be the fact mentioned above. Of course, the conclusion cannot be made from these preliminary results. More experimental data is required in order to confirm this trend.

Ignition Delay

It can be expected that the ignition of the slurry droplet will be delayed. The demonstration burns in utility bolilers of power stations and the experiments conducted in pilot plant furnaces have revealved this fact. Many methods to improve the ignition of CWS have been postulated. These include increasing the temperature of the combustion air, improving atomization quality, adopting new types of burners to improve the near field aerodynamics in the combustion chamber, and using special jets to create a stronger recirculating zone.

The delay in igniton of CWS in the boiler will move the flame

centre downstream or out from the combustion chamber. This not only causes unsteady operation and lower combustion efficiency, but also overheats the convective heat transfer surface. The droplets of CWS do not have sufficient time in the boiler for high conversion of combustible matter. This is why the investigations have focused on CWS since it was proposed as the replacement for heavy fuel oil. However, there is some evidence to indicate that the hollow char cenospheres formed in CWS combustion t end to accelerate mass transfer, which in turn decreases the residence time for combustion.

As seen from Tables 12, 13 and 14, under similar operational conditions, i.e., same furnace temperature profile and close size of droplet and particle, the conversion of moisture of pulverized coal had already reached 83.03 percent. Meanwhile, the conversion of moisture of the CWS droplet of 3.50 mm diameter was only 46.36 percent. For pulverized coal, themal decomposition of volatiles occurred and the conversion was as high as 60.90 percent. However, for the slurry droplet, devolatilization just started and the conversion remained at the low level of 14.41 percent. No doubt volatile decomposition plays a dominant role in the ignition of slurry droplets. Any delay of thermal decomposition of volatiles in the slurry droplet must cause a delay and difficulty of ignition. Evaporation of moisture in the slurry droplet is always a priority to the devolatilization and char combustion. The temperature level necessary for volatiles decompostion is established later due to the comsumption of heat for droplet evaporation..

Furthermore, the steam produced surrounds the droplet to form a steam-rich boundary layer. If the diameter of the slurry droplet is big enough and the external diffusion step governs the process, ignition of the slurry droplet will be further delayed.

Experimental observation shows that the bright, orange cloured granule from powdered fine coal could be seen visually when it appeared at the furnace bottom. It still smoked after reaching the collector. However, for slurry burning, only black and thick slury paste was found.

Unfortunately, the preliminary experiments did not produce any accurate quantitative information. The furnace facility cannot be adjusted to meet the requirement for various residence times of droplets in the furnace. The droplet size attainable is currently limited by the plugging of the hypodermic syringe. The method of collecting and quenching the droplets at the bottom of the furnace should be improved. Further work focusing on this area is necessary to better understand the single droplet combustion behaviour.

Overlappping of Combustion Processes

The overall combustion process of the coal particle or slurry droplet is a complex synthesis of physical and chemical reactions. Some reactions occur simultaneously, others successively. As commonly understood, the overall combustion process of the slurry droplet can be pictured as three individual processes: evaporation of moisture, thermal decomposition of volatiles and char residue combustion. But, they over lap to a certain degree. Now, the question is how much overlap exists. If the overlap between two successive processes is small, it can be ignored and the process treated as completely, independent (individual) successive processes. On the other hand, if they overlap each other heavily, one can consider them to occur simultaneously. So, it is important to know the degree of overlapping for analytical modelling.

In the early experimental work done for pulverized coal combustion, the overlapping between devolatilization and char combustion, 10 percent in most cases, should at least be considerd. Analytical (proximate) results showed that even though carbon conversion had reached 60 percent, the volatiles still could be found in the char. The results obtained in our experiments revealed that no matter what kind of droplet was tested, the overlapping between evaporation and devolatilization existed. The amount of conversion of volatiles was around 10 to 14 percent. Basically, the conversion of moisture reached 50 to 60 percent or more, depending on the furnace temperature profile and droplet size. However, the influence of these operating parameters on the conversion of volatiles does not seem to be as strong as the influence on the conversion of moisture. As to the overlapping between evaporation and char combustion, it can be ignored. For pulverized coal combustion and the reburning of dried droplets, the limited data showed that if the conversion of volatiles did not exceed 50 percent conversion of fixed carbon was only of the order of 1 - 1.5 percent. It can be concluded, in this case, that the char did not burn completly because some carbon content is included in the volatiles.

In order to model the combustion of slurry droplets and to apply the analysis to practical use with enough accuracy, successive steps are preferred instead of the simultaneous steps to simplify the mathematical treatments because the number of coupling equation can be reduced.

Influence of Droplet Size

For combustion, the size of the droplet or particle of fuel affects the overall process of combustion greatly, due to diffusional mass transfer control of the reaction regime. The size of the particle/droplet, at all times, is considered a major variable in the study of combustion phenomena. In our study, because the top size of the particles contained in the slurry could not be limited, the

droplet size generated was restricted to a narrow range (3.50 -4.00 mm in diameter), even though the data in Table 12 indicated that under the same residence time and furnace temperature profile, the droplet with a 3.50 mm diameter had a higher conversion of moisture than the bigger one (4.0 mm in diameter); almost 40 percent higher.

According to the approximate calculation for the 2.0 mm diameter slurry droplet (solid loading 60 percent), the evaporation time (conversion of moisture 98 percent) was 8 seconds at 1000°C and 11 seconds at 800°C. If droplet size is reduced to 100 micrometers, the time is shortened to 0.0074 sec at 1400°C and 0.006 sec at 1600°C. The correlation between evaporation time and droplet size is roughly as the second power of droplet diameter if convective heat transfer is dominant. For the combustion case, if the overall rate is controlled by the diffusion step, the influence of size on the reaction rate has a similar relation. So, if possible, the further investigation should focus on this topic.

COMPREHENSIVE COMMENTS

- The experimental method, including tube furnace and droplet generator, can be used in the study of single droplet combustion.

- The droplet size generated is basically dependent upon the needle (orifice) diameter. Currently, the residence time in the furnace is too short for the big droplet used to realize complete combustion.

- The preliminary results showed that a serious delay in droplet ignition was observed. Overlaps among evaporation, devolatilization and char combustion were observed.

- Droplet size has a great influence on the evaporation process.

- As many investigators observed, during evaporation and devolatilization, the agglomeration phenomena will affect the progress of combustion. Cenospheres will form. In our study, we have made no attempt to study the char combustion behaviour.

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